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Thermal radiation from large bolides and impact plumes

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Abstract

We have carried out numerical simulations of the impacts of asteroids and comets from 20 m to 3 km in diameter and calculated thermal radiation fluxes on the ground and luminous efficiencies. 50-m-diameter bodies can ignite forest fires within a radius of up to 40 km and 3-km asteroids – within 1700 km.

1. Introduction

Direct thermal radiation from superbolides or impact plumes can ignite fires over large areas: 200-500 km^2 in the case of the 1908 Tunguska airblast [e.g., 1] and 3-5% of the total Earth's surface in the Chicxulub impact event [2]. Thermal radiation damage in a general case can be estimated using an analogy with nuclear explosions and some values of luminous efficiency of hypervelocity impacts [3]. However, the luminous efficiency (fraction of impactor kinetic energy emitted as thermal radiation) is not well constrained and fireballs and impact plumes can significantly differ in shape and energy from nuclear explosions. Asteroid and comet hazards demand assessments that are more accurate, but determination of radiation intensity presents a problem associated with a great amount of computations.

2. Numerical technique

The simulations of impacts were carried out using a hydrodynamic model, equations, and a numerical technique described, e.g., in [4]. We assumed that the cosmic object has no strength, deforms, fragments, and vaporizes in the atmosphere. After the impact on the ground, formation of craters and plumes was simulated taking into account internal friction of destroyed rocks and a wake formed in the atmosphere. The equations of radiative transfer, added to the equations of gas dynamics, were used in the approximation of radiative heat diffusion or, if the Rosseland optical depth of a radiating volume of gas and vapor was less than unity, in the approximation of volume emission. We used temperature and density distributions obtained in the simulations to calculate radiation fluxes on the Earth's surface by integrating the equation of radiative transfer along rays passing through a luminous area. We used tables of the equation of state of dunite, quartz (for impactor and target) and air, and tables of absorption coefficients of ordinary chondrite vapor and air (see refs. in [4]).

3. Results of numerical simulations

In the case of the 2013 Chelyabinsk superbolide (20-m-diameter asteroid, entry angle to horizontal θ=19°), the maximum radiation flux on the ground is about 2.5 W/cm^2 and the maximum radiant exposure (thermal energy incident on a unit area) is about 3 J/cm^2, which is insufficient for palpable skin burns but can cause temporal flash blindness in agreement with the eyewitness reports. The calculated luminous efficiency η is 17%. For rough estimates one can use the approximation of a point light source located at an altitude of 30 km, however, at distances about 100 km from the point with maximum irradiation on the ground the radiant exposures can substantially differ, up to two times. Numerical simulations of an airburst caused by a 50-m-diameter stony asteroid (dunite, density 3.3 g/cm^3) entering the atmosphere at an angle of 45° with a velocity of 20 km/s (kinetic energy 10.4 Mt TNT) gave an altitude of an airburst about 10 km, η=3.5%, and an area of forest ignition (deciduous leaves or rotted wood) about 350 km^2, quite similar to the 1908 Tunguska event.

A series of simulations of bolides show that η grows if the body diameter D and the entry angle θ decrease. For a stony 30-m-diameter asteroid entering the atmosphere at 20 km/s η=19% if θ=15° and η=4.5% if θ=90°. For D=50 m η=14.5% if θ=15° and η=2.6% if θ=90°. For cometary bodies (water ice, density 1 g/cm^3) of the same sizes η is from 1.5 to 3 times bigger than for the stony bodies. The bodies with a diameter of 30 m do not carry a risk of fire, but 50-m-diameter bodies can ignite fires in areas with radii from 10 to 40 km, depending on their velocity. Bodies with D=100 m can produce fires within a radius of up to 100 km.

If an asteroid hits the ground, the main source of radiation is vaporized material of an asteroid and a target in the impact plume. The vapor heated to temperatures 2000-2500 K reaches heights about 300 km if D=1km (Fig. 1) and above 600 km if D=3 km. In contrast to bolides, luminous efficiency decreases with decreasing θ because for smaller θ less energy is transferred to the impact plume. E.g., for D=1 km η=13% if θ=60° and η=8% if θ=30°.

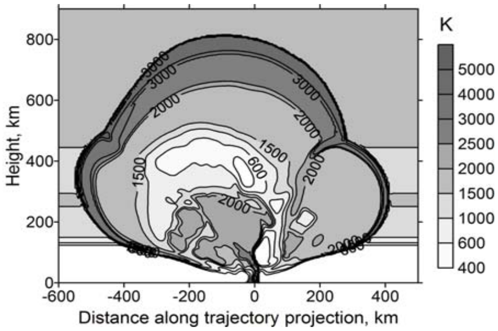

Figure 1: Isotherms in the atmosphere 80 s after the impact of a 1-km-diameter stony asteroid that entered the atmosphere at 45° with a velocity of 20 km/s and moved from right to left. The outer contour lines with temperatures above 3000 K correspond to a shock wave that accelerates upward but radiates only slightly because of a very low density of air.

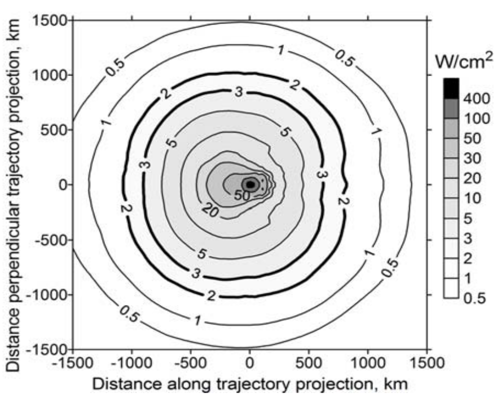

Figure 2: Contour lines of maximum radiation flux densities on the Earth's surface calculated for the impact shown in Fig. 1. It was assumed that atmospheric visibility is 30 km.

Duration of a thermal pulse from its beginning to its maximum τ is 100-150 s if D=1 km, in this case dry leaf litters can be ignited if maximum radiation flux density Q is 2-3 W/cm^2 [5]. As shown in Fig. 2, the average radius R of the area of potential fire ignition is 800-1000 km. If D=3 km, τ =200-250 s and live pine needles are ignited at Q~3-4 W/cm^2, R~1700 km.

4. Conclusions

Direct thermal radiation from fireballs and impact plumes produced by asteroids and comets larger than 50 m in diameter is dangerous for people, animals, plants, economic objects. Fires can be ignited on the ground within a radius of roughly 1000 times the body's diameter (for $D \leq 1$ km), and melted rocks could be found around impact craters on the Earth and terrestrial planets. During the Phanerozoic 1-km-diameter asteroids (that fall once in 1 My) could left about 500 craters with the traces of thermal radiation.

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